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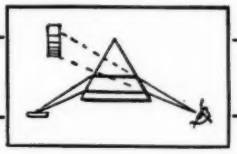

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Optics and the Glass Industry*

E. D. TILLYER
American Optical Company, Southbridge, Massachusetts
(Received December 13, 1937)

THE study of optics as well as the design and manufacture of optical and ophthalmological instruments requires the study of the necessary raw materials. The most important of these materials are the refracting media used in these instruments. For the purpose of this paper I am going to call any homogeneous refracting medium glass. Since glass is so very important to us we can't help feeling that we are important to the glass industry. In 1935 there was 2,300,000 tons of glass sand used, which would produce approximately 3,000,000 tons of glass. One tenth percent of this by weight, or even less, went into the production of all kinds of optical instruments, including ophthalmic lenses. Considering this, we cannot help feeling that as far as glass users go we are of relatively small importance, and yet we are very particular. We must have glasses having very special properties, and instead of feeling, as sometimes some people do, that the glass industry has slighted us, we should feel grateful to them for what they have done for us.

The early history of optical glass making has been well written up. An excellent account of it will be found in the *Encyclopedia Britannica*. In Hovestadt's *Jena Glass* will be found an excellent account of the early work by Schott, who tried many combinations of elements which had not been generally used in glasses. This was in the eighties, and was a result of a false demonstration that a high index glass with a low dispersion was necessary to produce a flat field anastigmatic photographic lens. Actually an anastigmatic lens has been made with the older glasses but it is advantageous to use the newer ones which were developed by Schott. The principal addition to the glass composition required in this case was barium, but an interesting thing is that even early in 1877 Charles Feil produced baryta glass as the result of experiments in collaboration with the chemist Fremy, so that we must not omit the contributions of the founders of the Parra-Mantois organization.

Let us briefly review some of the types of glasses that are desirable for optical instruments and for ophthalmological purposes, and some of the glasses which we would like to have. If we take any glass catalog we find we have a range of refractive indices from approximately 1.47 to 1.93, with a reciprocal relative dispersion ranging from 70 to 20. But unfortunately we haven't the low index glass with the same dispersion as the high index, or *vice versa*. This would be very nice if we had it. Also, if we examine the partial dispersions we find that with glass alone we cannot make a perfectly color-free lens combination, and it is necessary to go to the minerals,

* Invited paper delivered at the Symposium on Optical Materials held by the Optical Society of America at Lake Placid, New York, October 14–16, 1937.

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such as fluorite or lithium fluoride, to obtain the desired refractive properties. We would like to have the glasses stable both to light and the atmosphere, with just one more property, all having the same thermal expansion.

Optical glass is somewhat different from ophthalmological glass. They are approaching each other rapidly, except that the coefficient of expansion, for instance, in optical glass is of minor importance but is of utmost importance in many of the ophthalmological glasses. It wasn't many years ago that an advertisement of a photographic lens stated that the presence of bubbles was an indication of the good glasses used. Actually what was meant was that a barium glass was used. In bifocals today we use a barium glass corresponding to that used in photographic lenses. It must not have bubbles, and it must have two other properties, which the old photographic lens glass did not require. It must be matched in coefficient of expansion with a crown glass all the way from the fusion temperature down to room temperature, and it must not tarnish, because the public does not like the tarnish, although more light gets through the lens when it is tarnished slightly. Some of the ophthalmic crowns have an index tolerance of only three units in the fourth decimal place.

In addition to the variation of the refractive index required for optical purposes we desire absorption glasses which permit certain parts of the visual spectrum to pass, and cut off as sharply as possible other parts of the spectrum. An important use of these absorption glasses is for railroad signals, which are actually optical instruments.

For ophthalmological purposes we require glasses which cut off certain parts of the invisible spectrum, the ultraviolet and the infrared, or both. These glasses must be made so close to one another, melt after melt, that one can look at them edgewise and not see the difference in tint. Of course, the optical properties and the absorption in the invisible region of the spectrum, and the coefficient of expansion must be held constant.

Then there are the glasses for protection from high intensity sources, such as are used for welding. Twenty years ago there was only one commercial welding glass made that transmitted less than 25 percent of the total energy from a high intensity source. Now for the same optical density we would consider 0.01 percent total energy high. Some improvement in twenty years!

It might be well here to dream a little about what an optical designer would like to have in glass. Of course, one would be a glass with an exceedingly high index, with no dispersion whatever. That would save a lot of work, but obviously it is impossible, so for some purposes we would like to have a glass with a very high index of refraction and very low dispersion. For other purposes we would like to have a glass with an even higher index of refraction and considerable dispersion. As an illustration, take an achromatic telescope objective. If we could vary our dispersions properly, taking an ordinary crown for the convex component of a cemented objective, and a very high index flint for the other component, we have greatly reduced the chromatic variation of the spherical aberration, and then if the partial dispersions only ran parallel, we would have an apochromatic lens with just two components.

We would like to have glasses which are close together in their refractive properties but have different, and widely different, dispersions. We would like to have glasses which are widely different in their refractive properties and close together in their dispersions, and oh! for a glass whose partial ratio of dispersion was entirely different than anything we have today and still the refractive index and mean dispersion near one of our regular glasses. Then we could correct the secondary spectrum with ease, and without going to excessively steep curves or using various minerals.

For optical purposes, more than for ophthalmological purposes, we would like a glass which transmits like fluorite way into the infrared and ultraviolet. It would be very nice to have a stable prism which we could use on the infrared spectrometer instead of rocksalt, or a glass which we could use in place of quartz in the ultraviolet spectroscope. Of course, we could use fluorite and quartz if we could get the fluorite.

I have just read in Hovestadt's book, *Jena Glass*, "phosphate glasses are all hygroscopic," and then one of my associates comes and hands

me a glass with 75 percent phosphorous pentoxide in it and tells me it is less soluble in water than a high grade crown or borosilicate crown. I just don't know what to say, and then when he takes this same glass and dips it in hydrofluoric acid and it is untouched, I have decided that there is much to be learned.

Hygroscopic phosphate glasses have been produced for a long time. In general, they have the remarkable property of transmitting into the ultraviolet much further than any ordinary glass that I have yet seen. We measure the ultraviolet transmission at the 5 percent point for a 2 mm sample. We have obtained *stable* phosphate glasses which transmit to 233 mμ with a refractive index of 1.52 and a reciprocal relative dispersion of 70, on a laboratory scale. Without being quite so stable we have obtained glasses which transmit to 215 with a reciprocal relative dispersion of 75. Probably with purer materials the transmission would be still further into the ultraviolet. Silica seems to be a poison to some of these glasses. For future progress in many kinds of glasses we must eliminate silica and silicates.

The addition of very small quantities of many elements changes the stability very greatly. Likewise, the addition of some materials increases the transmission of a glass in the ultraviolet. As an example, a small quantity of tin oxide added to an ordinary crown batch often extends the transmission by 30 or 40 mμ farther into the ultraviolet. This is rather hard to understand, particularly when the iron content of the original glass batch is low to start with.

Another very interesting group of glasses is the zinc borates. The plain zinc borate glass has been known for a long time. The zinc borates in general have a refractive index of somewhere around 1.63 to 1.65 with a reciprocal relative dispersion of 50 to 55. They have been, in general, unstable, but beautiful sparkling glasses. We have studied modifications of these zinc borate glasses with various additions. One of the promising additions is beryllium oxide which does not change the refractive index or reciprocal relative dispersion to any extent, yet it makes a most beautiful high index, low dispersion glass of crystal clearness, almost good enough to be cut into gems, and it is very resistant to chemical attack. These zinc borates are also quite transparent in the ultraviolet, not as transparent as some of the phosphates, but more so than other glasses of corresponding index of refraction, let alone dispersion. In addition, they are free from bubbles even in laboratory melts. Other elements added to the zinc borate combination produce glasses having different properties. For instance, one zinc-borate strontium combination has an index of 1.60 with a reciprocal relative dispersion of, roughly, 64.

Now let us suppose that we change from zinc to some other material. Cadmium borate has a very high index, as if it were in the extra dense flint group, with a reciprocal relative dispersion like the barium glasses. Titanium in the zinc borates, raises the index very rapidly but produces a glass something like the baryta flints in dispersion, but with an even higher index of refraction. It is not as transparent in the ultraviolet as the ordinary zinc borates. This may be due to impurities which we have not yet determined.

A group of very high index glasses have been prepared by Kodak. These contain various combinations of zirconium, titanium, tantalum, lanthanum, tungsten, thorium, lithium and boron. The refractive indices range from 1.71 to 2.02, and the reciprocal relative dispersions from 54 to 19.

Recently there have been described by Dr. Heyne another group of glasses which have some quite remarkable properties. They are what he calls the beryllium fluoride glasses. These glasses have considerable transmission in the ultraviolet, according to published results, almost like the phosphates previously mentioned.

An interesting feature of these glasses is that they soften at a very low temperature, ranging something below 300°C as a rule, even down to 160°C. They are composed of beryllium fluoride with sodium fluoride, potassium fluoride, aluminum fluoride, magnesium fluoride or lithium fluoride, and sometimes some phosphate, substituted for some of the fluorides. They are not stable, *so far*. This is just another example of leaving silica out of a glass and obtaining some unique properties.

So far we have not said anything about coloring agents in these peculiar glasses. The ideal ultraviolet absorbent in an ordinary crown glass is cerium. Two percent of cerium added to almost

any ordinary glass will give a transmission of 5 percent at about 356 mμ for a thickness of 2 mm. When cerium is added to a phosphate glass one has a glass which is almost as transparent to the ultraviolet as ordinary glass. The transmission has been moved further into the ultraviolet about 30 to 40 mμ, and it doesn't seem to make much difference how much cerium is put in. Practically every coloring oxide gives an entirely different result in these glasses than in the ordinary glasses.

Stability in all glasses is important. For optical purposes we can often put a partially stable glass between two stable glasses. For spectacles we must have a stable glass to start with. This refers, of course, to stability to atmospheric conditions in ordinary use. We cannot always expect to make a glass stable under a chemical hood or in some peculiar industrial situations. Various additions to atmospherically unstable glass can be made, which will greatly increase its stability. Sometimes two or more addition agents will work much better than only one. Also, sometimes it seems to me that a regular shotgun preparation gives the best results, a little bit of everything thrown in together.

Thus far we have only talked about stability to atmospheric conditions. Stability to light is of equal importance. It isn't very nice to have a white piece of crown glass turn yellow when exposed to the sunlight for a while, or another piece turn a purplish-pink such as one can see in many old windows. Great care has to be exercised in getting glasses which are stable to light.

Recently there have been introduced a number of synthetic products which have an exceedingly high transmission, fully up to that of the best optical glass. One of these, Plexiglas, for the particular sample measured has a refractive index very near the ordinary crowns or just a little lower, reciprocal dispersion of about the same as the ordinary crowns, but a ratio of the partial dispersions like extra dense flints which seems to be very promising, to put it mildly. If these measurements are confirmed, then a new factor has been introduced in making a completely color-corrected lens system. Also, the light transmission extends out somewhat further in the ultraviolet than an ordinary crown glass which is favorable for an optical instrument. Others of these new synthetics have different refractive indices and different dispersions, and one beauty of it is that the refractive index can be made an independent variable by the use of addition agents and placed where desired over quite a range. Unfortunately, the reciprocal relative dispersion does change somewhat in the process but that can be shifted in other ways.

About the future of the new synthetics, I personally hate to predict. For exposed lenses they certainly do scratch. The material may have irregularities in the refractive index unless great care is used in manufacturing.

As to the future of optical glasses I would like to make no prediction. I think we have started, though, in increasing our range of refractive indices, dispersions and other optical properties.

It would not surprise me greatly at any time to see some of our ideals fulfilled. I do not expect to have the refractive index of the diamond but I do expect to see indices way beyond our lead glasses, and to have them with transmissions extending further into the ultraviolet. I expect to see absorption glasses way beyond our present demands, with sharp cut-offs at the region desired, and good transmission at other points.

Of course, I must include in glasses everything that may be used as a refracting medium in an optical system. I believe we are just at the beginning of a new era in materials to design a refracting system, instead of having reached the ultimate.

The Availability of Optical Glass in America*

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(Received December 11, 1937)

Optical glass is manufactured in the United States by one company only, but that company manufactures a wide range of glass types and could produce any additional types for which a demand might develop. Blanks for prisms and refractor lenses of moderate size are available from the same source; larger sizes probably could be obtained, but only on special order. Disks for reflecting telescopes are not made of optical glass, and methods for manufacturing them have been developed by one of our leading glass companies. As a result, the manufacture of reflector disks of the largest size has been put on a production basis. The characteristics of optical glass are made clear by a short discussion.

OPTICAL glass is the material available to the designer for the calculation and construction of lens systems in which the many possible defects and aberrations are reduced to a minimum. It is characterized by the perfection of certain physical properties, obtained by extreme care in manufacture, and by a wide range of optical properties, obtained by change in composition.

The physical properties which characterize optical glass are almost perfect homogeneity and high transparency. Freedom from bubbles is also important, but in this respect optical glass does not differ from other types of glass such as ophthalmic glass or even plate glass, and for many uses a few small bubbles do no harm and are less objectionable than in plate glass.

A lack of homogeneity is indicated by a variability of refractive index, and may be of two sorts. The more serious is caused by regions or streaks different in chemical composition, resulting in what are known as ream, cord, or striae. Freedom from striae is the most important characteristic of optical glass, and the technique of obtaining striae-free glass is difficult to master. Also, complete freedom from striae, perfect homogeneity, is a goal probably unattainable, and in practice it is necessary to compromise in accepting optical glass which is sufficiently free from striae for the purpose intended. In some lens systems, not too coarse striae normal to the light path are not objectionable. Frequently a single coarse stria will do no harm—except for a slight loss of light—in a lens element in which fine striae would prove ruinous. Other uses, such as prisms for periscopes, tax to the utmost the ability of the glassmaker to approach perfection, and require unremitting care and diligence. Even under the best of manufacturing conditions the yield of striae-free glass is only twenty to twenty-five percent of the glass melted.

The other type of inhomogeneity is caused by differences in the thermal history of different parts of a piece of glass, resulting in gradual change in refractive index. This trouble is almost a second-order effect, is never met with in glass as it comes from the pot, but is caused by improper heat treatment, and can be removed by proper heat treatment.

High transmissivity of light is an important characteristic of optical glass, obtained only by careful attention to many details. A low transmissivity usually is caused by iron oxide in the glass, which produces characteristic and objectionable color. In the older glasses this was overcome by introducing a decolorizer which has a complementary absorption, usually manganese oxide. Unfortunately, both the iron and the manganese absorb light and thus reduce the amount transmitted through the glass. The use of decolorizer is now unnecessary because the raw materials for glass-making have greatly improved in quality. Ordinary window glass today is of better quality than some pre-war optical glass, chiefly because of the reduction in iron content of the sand. Sand containing less than 0.01 percent of iron oxide is now available and commonly used. Throughout the manufacture of optical glass the greatest care is

* Invited paper delivered at the Symposium on Optical Materials held by the Optical Society of America at Lake Placid, New York, October 14–16, 1937.

necessary in all details; it is a laboratory process carried out on a commercial scale.

Optical glass is available in a wide range of refractive index and dispersion, and to a limited extent these two properties are independently variable. This is not true of what are called the "older" types, and is chiefly the result of the introduction of barium oxide.

The older crown-flint series had almost a linear relation between refractive index and dispersion, and hence the possible reduction of chromatic aberration was limited. At the bottom of the series was the "ordinary" crown, a soda-lime silica glass essentially the same in composition as window glass. A small change in the dispersion ratios can be obtained by substituting zinc oxide for some of the lime, producing the zinc crowns, and small amounts of barium oxide are used in some crowns.

The introduction of the borosilicate crowns extended the range to lower index, and the effect of the boric oxide in lengthening the red end of the spectrum is especially useful in reducing the secondary spectrum when used in connection with the flint glasses, whose content of lead oxide lengthens the blue. Of later introduction are the fluor crowns, which still further extend the series to lower index, and some of the fluor crowns produce significant changes in the index-dispersion relations.

The optical glasses called flints all contain lead oxide. The soft crowns are transition members of the series, between the crowns and flints. They are somewhat inferior in chemical durability to the crowns and flints. Telescope crown is a special glass in this general region, characterized by the presence of a large amount of antimony oxide.

The flints proper range through the light and medium flints, with refractive indices from about 1.55 to 1.65, to the dense and extra-dense flints, with indices up to 1.8 or even higher. The content of lead oxide ranges from about thirty to eighty percent, and the higher members of the series commonly contain only potash, lead oxide, and silica, with a little arsenic.

The entire crown-flint series of glasses offer limited opportunities for correcting the secondary spectrum, but the introduction of barium oxide gives glasses differing from the crown-flint series in a notable decrease in dispersion. They are grouped into the light barium crowns, dense barium crowns, and barium flints. A typical light barium crown has an index of about 1.575, and a dispersion, C to F, of 99×10^{-4}; a light flint of the same index has a dispersion 140×10^{-4}. A typical dense barium crown, of the type frequently used in high speed anastigmats, has an index of about 1.61, a dispersion of about 110×10^{-4}; a flint of the same index has about 166×10^{-4}. The barium flints have smaller dispersion than the corresponding "ordinary" flint glasses.

The range of possible glass compositions is definitely limited by chemical factors. All glasses on cooling from the melting temperature pass through a temperature range in which the liquid becomes unstable with respect to one or more crystalline components, and at or below this temperature the glass can be devitrified by appropriate heat treatment. If during the working or annealing process the glass is held too long in the temperature range in which crystallization takes place most readily, it will devitrify and be ruined. The tendency toward crystallization is the chief factor which limits the composition range of practical glasses, and it imposes limitations which are impassable. A greater independence between refractive index and dispersion in optical glasses is greatly to be desired, but the possibilities are sharply limited by chemical relationships.

The optical glass industry in this country at the close of the war had developed a tremendous potential capacity. The types of glass manufactured were limited to those few which are the irreducible minimum for military needs, far fewer than are needed for general optical purposes. Four firms were engaged in the manufacture of optical glass: Bausch and Lomb Optical Company, Keuffel and Esser Company, Pittsburgh Plate Glass Company, and Spencer Lens Company.

Bausch and Lomb Optical Company is the only firm manufacturing optical glass in this country today, and it is to its catalog that we must turn for our available optical glass. The latest available catalog of Schott and Genossen offers 160 varieties of optical glass; that of Parra-Mantois, 201 types; of Chance Brothers, 69; Bausch and Lomb, 22. At first this seems a surprising difference, but in reality it is an

unfair comparison. The catalogs of the older companies contain numerous varieties of the same types of glass, varieties differing little from each other in composition and properties, and not at all in difficulty of manufacture.

The manufacture of optical glass is a small-scale business. The total import of optical glass for the first 11 months of 1936 was 192,505 pounds, valued at $195,130. Estimates of the domestic manufacture are not available, but doubtless it was much smaller than the imports. So small a business needs a sponsor; in other countries it is a unit of a large-scale glass manufacture, and in this country the sole producer is a large-scale manufacturer of optical instruments. That manufacturer presumably makes the glasses for which there is a demand, either in the parent factory or in the open market, and there would be no reason for the multiplication of variants of those types. Without doubt, should sufficient demand develop for additional varieties, there would be no difficulty in producing them; and without doubt the types made will increase as the demand increases, but a manufacturer cannot be expected to make a 1500-pound melting to fill an order for a pound of glass.

Most users of optical glass require comparatively small pieces; some require lenses or prisms of larger size, possibly six or even ten inches in diameter. In the manufacture of optical glass the melt breaks on cooling into pieces of considerable size, which must be further broken for inspection and molding into slabs. During this inspection, if demand exists for larger pieces, such as required for 10-inch lenses or prisms, commonly there is no difficulty in selecting suitable pieces. The question has been asked if optical glass is available for large lenses—say, for example, a 25-inch refractor lens. In any factory a piece of suitable size would be the result of careful watchfulness over a period of time, and some luck; but in any factory making the type of glass required on a large scale, suitable pieces would be found occasionally, if one were looking for them, and not breaking up the glass into pieces suitable for usual production. The probability of a demand for such pieces is not great.

The production of ophthalmic glass is much larger than that of optical glass, and most of its requirements of physical perfection are less stringent. No striae are admissible which would be visible when viewed through the surface of the finished lens, but not too coarse striae parallel to the surface are not visible and do no harm. Optical glass appears perfectly homogeneous when viewed edge-on; ophthalmic glass may show numerous striae. However, there are many uses in optical instruments for which a good grade of ophthalmic glass is suitable.

The types of glass used in ophthalmic work are small as compared with optical glass. The commonest spectacle glass is similar in composition and properties to an ordinary crown; it is one of the ordinary crowns. Flint glasses are used for bifocals; a flint of index of about 1.616 most commonly, rarely one of 1.65 or even higher. Other types of ophthalmic glass are the numerous tints, ranging from a light smoke or a light Crookes glass to almost opaque welders' glasses. All these are made in this country, and ophthalmic glass is available in any quantity and of the highest quality.

The gigantic 200-inch disk made by the Corning Glass Works for the new Palomar Observatory has had much publicity, but the public has not been aware that this is only the most spectacular product of a new industry. Besides the eight disks supplementary to the 200-inch, all of which are of "ribbed" structure, and one of which, the 120-inch flat, is larger than any disk previously made, there have been made in Corning seven solid type disks for reflecting telescopes. These are: a 24-inch for Cornell University; a 30-inch and a 36-inch for the Foundation for Astrophysical Research; a 60-inch for Harvard University; a 76-inch for the University of Toronto; an 81-inch for McDonald Observatory, Texas; and a 98-inch for the University of Michigan. The glass used for this purpose is not an optical glass. It does not transmit light, but merely serves to give a figure to, and support, the aluminum coating which reflects the light. It does require a glass of special composition; a glass of small coefficient of expansion to minimize the changes of figure caused by changes in temperature, and of unusual resistance to devitrification to remain a glass during the long annealing period. These and other problems have been solved, and the production of mirrors for reflecting telescopes, of any size, is a routine matter.

Optical Glass Requirements of the Optical Industry*

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(Received December 11, 1937)

After defining optical glass, the requirements of the optical industry are discussed from the standpoints of quantity, quality, and variety. Consumption is small but the demands in respect of quality are high. The variety of optical constants now available is great but the designer is in need of combinations of index of refraction and dispersion not now available.

AFTER geometrical optics had advanced to the point where the nature of aberrations was understood and methods had been devised whereby they could be eliminated it became apparent that the quality of the images formed by optical instruments depended not only on lens design and on perfection of workmanship, but on the homogeneity of the glass. Efforts were promptly made to improve the quality of glass intended for use in image-forming instruments thus establishing optical glass as a material differentiated from ordinary glass and for seventy-five years optical glass differed from ordinary glass essentially in this one respect only. It is true that there was more than one kind of glass available but the assortment was limited to two or three kinds of crown glass and a few flints, the principal ambition of the optical glass maker in respect of variety consisting in trying to make denser and denser flint glasses.

The first differentiation then between ordinary and optical glass was made on the basis of quality and it seems to me still the most fundamental difference. A second basis for differentiation seems to me to lie in the reproducibility of optical constants. While the maker of window glass, bottles, or insulators may achieve a very respectable constancy in index of refraction, it is incidental. He is not concerned about it and is not striving for either constancy or any predetermined or specified values. A committee of this society spent many hours of discussion and carried out an extended correspondence in an effort to formulate a definition of optical glass without conspicuous success. Presumably such a definition should permit one to determine by inspection whether a sample piece of glass is optical glass or not. A definition in that sense is impossible. Certain specimens might be broken out of electric insulators that might, if judged only on a quality basis, be classed as the finest optical glass while other specimens of glass, very difficult to produce at all because of the extraordinary optical properties prescribed, would be immediately classed as ordinary glass of poor grade.

For the purpose of this discussion we shall regard optical glass, therefore, as a material made to conform to specified optical properties and of a degree of physical excellence as high as can be reached in the kind of glass in question. What we mean by physical excellence will be discussed more fully a little later.

The glass requirements of the optical industry can be discussed from the standpoint of quantity, quality, and variety.

QUANTITY

Merely for the sake of enabling you to place the size of the optical glass subject somewhere between the consumption of platinum and the consumption of pig iron, I have made the following estimates.

Of strictly optical glass the consumption in this country probably amounts to 75,000 lbs. per year. This may be wrong by 25 or 30 percent. This year the quantity is likely to be more rather than less.

Of spectacle glass which is of a grade intermediate between ordinary glass and the highest grade optical glass, the consumption probably amounts to 2,500,000 lbs.

Compared with the production of steel this is insignificant business but without the optical glass the steel business would not be what it is.

* Invited paper delivered at the Symposium on Optical Materials held by the Optical Society of America at Lake Placid, New York, October 14–16, 1937.

This is not the place, nor does this audience require the digression into the importance of this little quantity of glass to our current mode and standard of living, although the temptation is great.

Quality

We can perhaps spend our time more profitably by turning to a consideration of what we mean by the physical excellence referred to earlier.

After the lens maker of 1800 had designed a lens to be reasonably free from spherical and chromatic aberrations and had done his utmost to grind the lens with truly spherical surfaces, he usually found the image lacking in sharpness and in contrast. This effect was due primarily to inhomogeneity of the glass in respect of refractive index. The inhomogeneities existing in the glass might be abrupt leading to visible streaks or striae or it might be a gradual change from one side to another in the block of glass. The former are conspicuous and probably the more serious.

The methods that have been devised to produce glass free from striae have been discussed by Dr. Morey and Mr. Finn.

The first thing the manufacturer of fine lenses demands, then, is homogeneous glass, glass that is free from streaks of material whose detection is in itself proof that they have an index of refraction slightly different from the surrounding glass. It is difficult to determine by inspection just how serious in its effect on image quality will be a single heavy stria or a group of fine ones. In general the single heavy one is likely to be less dangerous than several fine ones. It would simplify matters if we could summarily reject all glass in which any striae could be detected but this is impractical for it may really be questioned whether absolutely homogeneous glass has ever been produced. There is a nice problem, therefore, in the processing of glass, in deciding what to accept and what to reject. We use in our own glass plant a method of inspection for striae that leads to astonishing rejections when it is applied to glass obtained from foreign sources of supply. Perhaps we are rejecting good glass and on the other hand perhaps we are not yet inspecting rigidly enough. We know we could increase the sensitivity of the method still more and reject still more glass if it is necessary but on the other hand the more rigid the inspection, the higher the cost of the glass. On the one hand we do not wish to reject glass that has cost five or six dollars per pound if it will make good lenses and on the other hand we do not want to pay skilled artisans to work on glass whose quality is such that in spite of their best efforts the piece will have to be rejected. Assuming that we cannot hope for absolutely homogeneous melts of glass, the next best thing would be a method of selection that would infallibly distinguish between good and bad glass.

In the consumer's mind, bubbles in glass are very offensive although from the optical standpoint they are the most harmless thing in the world. Bubbles are due to the volatilization of some of the materials in the batch in the melting process and because of greater viscosity they are held by some glasses much more tenaciously than by others. The manufacturer would like to take advantage of the more desirable optical properties of these glasses many times when he is compelled to use a less desirable glass because it is free of bubbles. Because of the refusal of the consuming public to accept bubbles in glass, he pays more for optical instruments than would otherwise be necessary and sometimes has to accept inferior performance.

From the viewpoint of the manufacturer of optical instruments a very important factor in the quality of the glass is its condition with reference to freedom from strain. Freedom from strain is the result of careful annealing. In one sense, the condition of strain within a piece of glass might be dismissed as unrelated to its physical quality for the same piece of glass may be strained and annealed as many times as we please by suitable heat treatment. Annealing is a process of workmanship of much the same class as polishing a surface on the glass. The lens maker, however, regards it as a matter of glass quality and we will follow his example. In respect of annealing, as well as inspection for striae, our ideas have been revised within the last few years and we now regard it as uneconomical to spend valuable time trying to put good surfaces on glass whose freedom from strain is open to any question. Fortunately the process of annealing is pretty well understood and the production of

glass free from strain is not an impossibility. It is tedious and expensive but otherwise offers no difficulty. The principal effect of strain in glass seems to consist in preventing the formation of good surfaces. Apparently, glass that is strained changes form with change in temperature and perhaps even with time in unchanging temperature. Changing form with change in temperature is serious in the process of making a lens for it gets pretty warm in the polishing process. In the case of large prisms with considerable glass path, the crystalline nature of the strained glass block has in itself a degrading effect on image quality.

The manufacturer, of course, wants his glass to be as transparent as possible. Twenty-five years ago an absorption of light of one percent per centimeter was regarded as excellent quality. Much of the glass made in this country during the war absorbed two or more percent per centimeter. The best glass today absorbs not more than four to six tenths of a percent per centimeter except in the dense barium crowns and the densest flint glasses. In general, however, the glass maker has approached pretty close to perfection in this respect.

The remaining factor governing quality that I wish to mention is the resistance of polished surfaces to the attacks of destructive agencies carried in the air. Insofar as I know, the durability of a polished surface on glass depends solely on the chemical composition of the glass. So, also, do the optical properties of the glass. In general, then, the durability of polished surfaces must be related to optical properties. This is not strictly true, fortunately, for glasses can be produced meeting given specifications for optical properties that differ considerably in their resistance to atmospheric attack. Two principal varieties of surface deterioration are encountered. First, and less serious, is the development of a sort of metallic luster generally known as tarnish. H. Dennis Taylor discovered to his surprise years ago that tarnished surfaces had a greater light transmission and a lower Fresnel reflection than clean, freshly-polished surfaces. Except for the appearance, then, which creates uneasiness in the mind of the owner or sales resistance in the prospective purchaser, this effect is not serious. This phenomenon is exhibited by glasses with very high lead content and by dense barium crowns.

The other class of effects is due to the sensitiveness of the glass to water. Some glasses are hygroscopic and collect small droplets of liquid on the surface, corroding the latter and destroying the polish. Others stain as a result of contact with water without the appearance of the small droplets. I do not know just what physical or chemical change is presented by these stains. The disposition to their formation seems to change remarkably with small differences in composition.

The reagents responsible for these effects are for the most part air-borne acids and water. Many efforts have been made to express by some numerical coefficient the surface resistance of glasses to such attack without much success. Any test that can be devised is a test of the resistance of the glass to that one reagent but to perhaps no other. It is my own opinion that the most sensible test is an exposure of a few months to the open air in a position where the samples collect a reasonable amount of dust but are protected against direct rain or snow. One melt will not differ appreciably from another of the same type of glass made from the same formula so that once tested and found satisfactory, further tests should be unnecessary unless a change is made in the formula. A problem is presented, of course, in setting up a scale according to which the specimen can be rated but this presents no impossible problem. What the optical instrument manufacturer is asking for is a series of glasses exhibiting all the desired optical properties and all with the surface durability of quartz. He is not likely to get it but improvements have been made and it may be hoped will continue.

Insofar as quality is concerned, then, the optical instrument manufacturer's requirements might be summed up as follows:

1. He would like an absolutely homogeneous glass, i.e., one completely free from variations in refractive index either abrupt or gradual.
2. He would like glass free from bubbles.
3. He would like glass absolutely transparent over the whole visible spectrum.
4. He would like glass completely free from strain.

5. He would like glass that in spite of the optical properties demanded was resistant to all the acids, alkalis, and water vapor encountered in both the usual outdoors and ordinary laboratory atmospheres.

As compared to the glasses available to Dolland for the manufacture of his first achromatic lenses, the glass maker is practically at the threshold of perfection with reference to the first three of these requirements. Dolland never knew of the glasses that give the most of our trouble in reference to the fifth point so our starting point for comparison must be taken in more recent times. Practically all fruitful experiments in the direction of expanding the list of glasses have been carried on in the last sixty years and it may not be too much to hope that greater stability can yet be achieved than we have at present.

Variety

I have already pointed out that the discovery of methods of eliminating aberrations brought about a demand for better glass. After this problem had been solved satisfactorily enough for the need of the day the next demand was for a wider choice in refractive index and dispersive powers but up until the time of Professor Abbe this resulted principally in the production of denser flint glasses with higher refractive indices. Seidel in 1856 and Petzval in 1857 asked for glass of high index of refraction and low dispersion for use in photographic lens design and in 1883 Abbe voiced the need for glasses exhibiting a choice of dispersive powers with about the same index of refraction, glasses of the same dispersive powers and different indices of refraction and, above all, flint glasses whose dispersions should be geometrically similar to crown glasses. Abbe's principal interest in making this demand was in the improvement of the image in the microscope through the reduction of the residual chromatic aberration or secondary spectrum.

The theory of secondary spectrum has been presented so many times and is available in so many sources of reference that there is no justification for repeating it here. Hopes for relief in the direction of producing flint glasses whose dispersions should be geometrically similar to those of crown glasses have not been realized in any outstanding degree. The perfection of the microscope has been accomplished by judicious combinations of glasses with more or less normal dispersions, aided by more skillful use of lens separations and especially by the use of crystalline fluorite.

But even if the efforts of Abbe and Schott have failed to relieve the designer as much as was hoped in respect of chromatic correction, they have permitted him to produce lenses simultaneously free from spherical aberration, coma, astigmatism and curvature of field. Photographic lenses of today include lenses with a relative aperture of f:1.5 that give excellent images over a field of upwards of 50° and lenses with a relative aperture of f:6.3 that cover 90° of field with excellent definition and extraordinary freedom from distortion. It is extremely unlikely that such results could have been achieved with the glasses of 1870.

The number of varieties of glass available is very large, probably larger than is necessary. In Schott's catalog of 1902, sixty-eight varieties of glass were included; their latest list includes 159 varieties. Some of these are so close to others that they are obviously accidental variants rather than the result of deliberate attempts to produce them. The availability of this wide selection does reduce the designer's labors, although at the cost of a larger inventory of glass to be carried in stock. Since the designer's employer is not ordinarily able to take issue with his statements as to how many kinds of glass he must have to produce results, he is naturally tempted to shift as much as he can of his burdens onto the shoulders of the glass maker.

Glass is available with an index of refraction as low as 1.465 and as high as 1.923 with almost any desired value between these limits. The glass of 1.92 index has very undesirable physical properties and is extremely expensive. Glasses of higher index with good physical properties would be useful in refractometry while barium crowns of still higher index and a wider range of low index medium flints would be very useful in lens design.

From the standpoint of accomplishment there is no justification for the glass maker to rest on his oars in the matter of producing crowns and flints with similar dispersions, the problem undertaken by Abbe and Schott.

In microscopy, we could use glasses or glass-like substances transparent in the short wave ultraviolet with higher index and higher dispersion than fluorite or lithium fluoride.

Perhaps we should add that the optical industry needs an unbreakable glass. Such a glass, if it possessed the other necessary characteristics, would be welcomed for uses in protective goggles or in spectacles to be worn by people engaged in hazardous occupations.

Perhaps the synthetic materials referred to by Dr. Tillyer may turn out to be useful in this application but at present they seem to be too soft for use in exposed positions. They have high transparency and low specific gravity, both desirable characteristics. They are probably less expensive than glass but unless they can more closely approach some of the other characteristics of glass, their optical future does not look too bright.

Optical Glass at the National Bureau of Standards*†

A. N. Finn
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(Received December 11, 1937)

A brief resumé is given of the work done by the National Bureau of Standards in connection with the manufacture of optical glass. The method of inspection for striae is outlined, data on the reproducibility of refractivity, from melt to melt, are given, and some effects of annealing on refractivity are mentioned. Attention is directed to the fact that the raw materials needed for the manufacture of optical glass are all domestically available.

THE ideas I wish to convey to you will relate to the manufacture of optical glass for precision instruments, as conducted at the National Bureau of Standards, and to some differences between our procedures and those of other manufacturers of optical glass.

As nearly as I can determine, the first manufacturer of optical glass in America was the Manhattan Optical Company of Cresskill, N. J., whose specialty was lenses for photographic purposes. Optical glass production was started there in 1894 and continued for about six years when the Manhattan Optical Company combined with Gundlach and the glass plant ceased operations.

The inception of this glass factory is not without interest. Dr. Hugo Schroeder, an optical instrument maker of Hamburg, came to America in 1893, after having been associated with Ross in London, to work with the Manhattan Optical Company. He was acquainted with both E. and C. Feil, who were great grandsons of P. L. Guinand of Neufchâtel (an associate of Fraunhofer and Utzschneider), and who established the company which is now the firm of Parra-Mantois. The son of C. Feil came to America about 1892. Schroeder induced the Manhattan Optical Company to make their own glass and for this purpose he recommended they secure the services of the younger Feil, who presumably had the "secrets" of his father's plant in France. Thus, it seems that the first American venture in the manufacture of optical glass was undertaken with the assistance of a direct descendant (the great-great-grandson) of P. L. Guinand, one of the earliest workers in the field.

Dr. S. W. Stratton, the first director of the National Bureau of Standards, was interested in experimental and applied optics to such an extent that he maintained direct supervision of all the Bureau's activities in optics until 1919. His interest in optics induced a keen interest in the manufacture and procurement of optical glass. He recognized the need of a domestic source of optical glass of various kinds and for different purposes, not only to supply the needs of the government but also to meet the demands of domestic manufacturers of optical instruments. Dr. Stratton planned to start preliminary work on the manufacture of optical glass as early as 1910, but was unable actually to begin the work until July, 1914, when C. C. Rand was employed to begin a study of optical glass technology under the direction of P. H. Bates, at the Pittsburgh branch of the Bureau. In the meantime (about 1912) the Bausch & Lomb Optical Company started work in the same field.

Consequently, when the World War started, some experimental work had already been done and some glass produced. By the time the United States became involved in that war, the foundation had already been laid for making optical glass, but quantity production had not been realized.

It is not necessary to describe the hectic period during the latter part of 1917 and the early part of 1918, when it became necessary to start with a limited amount of experience and make a lot of optical glass for fire-control instruments for our armed forces. Suffice it to say that satisfactory results were obtained through the untiring efforts of some of our trained chemists and

* Publication approved by the Director of the National Bureau of Standards of the U. S. Department of Commerce.
† Invited paper delivered at the Symposium on Optical Materials held by the Optical Society of America at Lake Placid, New York, October 14–16, 1937.

ceramists in the National Bureau of Standards, the Bausch & Lomb Optical Company, the Geophysical Laboratory, the Pittsburgh Plate Glass Company, and the Hazel-Atlas Glass Company.

Since those trying war days the manufacture of optical glass in America has been carried on, largely by the Bausch & Lomb Optical Company and the National Bureau of Standards. Although Dr. Stratton's original idea was to make glass for both industry and the government, it was finally deemed expedient to confine our activities to some of the requirements of the Government.

The reason this work is being continued at the Bureau is, then, to insure the federal government of an adequate supply of glass for fire-control instruments for any emergency that may arise. It is our function, in addition to our work on ordinary glass, continuously to study the problem so that we may be able definitely to describe all the operations necessary to insure a satisfactory supply of optical glass, and to keep a small force in training so that initial mass production will not be seriously delayed, should an emergency arise.

One cannot make optical glass without having something to melt it in—hence, the first requirement is "pots." As early as 1914, A. V. Bleininger realized the need of pots satisfactory for making optical glass, and undertook to develop such pots and a method for making them, of domestic ball clays and kaolins. As a result of his work, we now make all our own pots by the casting method developed by him at the Pittsburgh branch of the Bureau.[1] We think "cast" pots are more satisfactory for our purpose than the pots built up by hand, but for some purposes the handmade pots may have advantages. The clays from which the pots are made are all domestic and come chiefly from Kentucky, North Carolina, Delaware, Georgia, and Tennessee. No great change has been made in the composition of the pots during the past fifteen years, but some changes have been made in the size, nature and distribution of the grog. Contrary to generally accepted practice, we do not think it necessary to "age" the pots for a great length of time, although the majority of the pots we use are at least six months old. However, when occasion demands, we do successfully use pots that are only three or four weeks old. In the latter case, however, the pots are preheated at a slower rate than that normally employed. Furthermore, all pots are heated to approximately 1425°C and kept at this temperature for several hours before transferring them from the pot arches to the melting furnace. We feel that this makes the pot more resistant to glass attack than arching to a lower temperature and finishing the heating in a short time in the melting furnace, as is the practice in some plants. Our pots are about 20 inches deep and 25 inches in diameter, inside, and hold from 800 to 1200 pounds of glass, depending on its density. After the glass has been removed from the pot, the "pot shell" is carefully freed from adhering glass and, after crushing and sizing, is used for grog in new pots.

Our domestic deposits of clays are adequate for making pots, and we have satisfactory domestic deposits or sources of most of the batch materials required for making optical glass. However, there is, at present, no strictly domestic source of barium carbonate or potassium nitrate. During the World War, American manufacturers did produce the barium and potash salts, but the quality and quantity were not all that might be desired. Recently one domestic manufacturer has been making a satisfactory grade of barium hydroxide which can be substituted for the carbonate, and others have been marketing excellent potassium carbonate. The conversion of the latter to the nitrate, which is necessary for oxidation, presents no serious difficulty (although it is not being done at present). It may be safely stated, then, that, in case of need, all the necessary materials for making optical glass can be obtained domestically, and that we are economically independent of foreign sources of supply.

The raw materials from which our glass is made are bought on specification, the chief requirement being a low iron content. Since we make careful analyses of all our batch materials when received, and check them as may be deemed necessary during storage, corrections for vari-

[1] A. V. Bleininger, "Special pots for the melting of optical glass," J. Am. Cer. Soc. **1**, 15 (1918). F. H. Riddle, "The equipment of a casting plant for the manufacture of glass pots," J. Am. Cer. Soc. **2**, 647 (1919). J. W. Wright and D. H. Fuller, "Notes on the casting of porcelain glass pots," J. Am. Cer. Soc. **2**, 659 (1919). D. H. Fuller, "Note on porcelain glass pot mixtures," J. Am. Cer. Soc. **3**, 569 (1920). R. F. Geller and A. N. Finn, "Further studies on cast glass pots," J. Am. Cer. Soc. **6**, 865 (1923).

ations in amounts of essential ingredients present are easily made.

Except for minor changes, optical glass is melted and stirred in about the same way as it was during the war. A very comprehensive description of the operations involved has been given by Fenner[2] and Wright.[3] However, a significant change has been made in the time required for making a pot of glass.

During the war, G. W. Morey[4] made some changes in melting procedures by means of which the time required for melting a pot of glass could be reduced. We have continued work along this line and can now successfully make a melt of borosilicate crown in 14 hours and the other glasses in not to exceed 24 hours. Fifteen years ago, 36 or even 48 hours was not regarded as an unreasonable length of time for melting a pot of glass.

TABLE I.

INDEX (n_d) REQUIRED	NUMBER OF MELTS MADE	AVERAGE INDEX FOUND	MAXIMUM DEPARTURE FROM INDEX REQUIRED, $\times(10)^6$	
			+	−
1.517	157	1.51677	54	87
1.574	69	1.57393	288	163
1.620	23	1.62067	167	93
1.648	16	1.64869	248	126
1.605	2	1.60385	—	168*

* In this case, both values were less than the required 1.605.

After the cold glass has been separated from the pot, it is inspected. Stones, bubbles and seeds, which are sometimes present, are easily detected. The most troublesome condition an optical glass manufacturer has to contend with is striae. The detection of striae and the elimination of those parts of the glass containing striae is a problem of much concern to the manufacturer.

There are no great difficulties involved in the detection of striae after the surfaces of the glass have been polished—the Toepler method, the knife-edge method or the concave mirror test, modified or adapted to meet the requirements of the situation, may be used. But all of these presuppose polished faces, the ordinary prerequisite for which is the preparation of rectangular blocks made by "slabbing" the glass in molds—these operations (slabbing and polishing) require considerable time and consequently delay inspection.

In our work, all the glass is tested for striae by a modification of the immersion method described by Dodd.[5] This method enables us to inspect the irregularly shaped pieces of glass as they come from the pot, without any intermediate operations. The apparatus required consists essentially of a tank with plate glass windows through which a beam of slightly converging light is passed and then collected and focused for the inspector's eye. The light is rendered essentially homogeneous by passing it through a "carbon bisulphide prism" or a green filter described by Gibson.[6] The liquid in the tank has approximately the same refractivity as that of the glass being tested and usually consists of a mixture of mono-chlor-benzene and either kerosene or carbon bisulphide. Although inspection by immersion requires considerable practice, we are convinced that results obtained by trained inspectors are eminently satisfactory. It is true that fine striae are sometimes overlooked but this happens so infrequently that we have no complaints from the agencies using our glass.

With regard to reproducibility of index, we are frequently asked how closely our glasses conform to the prescribed index of refraction. Table I gives a summary of all the glasses made during the last five years. From this table it is evident that we make more 1.517 glass (borosilicate crown) than all the rest combined. Also, the departures from the required index are less than for the other glasses. The most probable reason for this is that we have adopted a rather definite time-temperature schedule for making borosilicate crown.

Our success in making the other glasses has not been so consistently uniform and we are still

[2] C. N. Fenner, "The technique of optical glass melting," J. Am. Cer. Soc. **2**, 102 (1919).

[3] F. E. Wright, "The manufacture of optical glass and of optical systems." Ordnance Department Document No. 2037. (Government Printing Office, Washington, D. C.)

[4] G. W. Morey, "An improved method of optical glass manufacture," J. Am. Cer. Soc. **2**, 146 (1919).

[5] L. E. Dodd, "Comparison tests for striae in optical glass, by the Brashear converging light, direct view method, the Bureau of Standards tank immersion method, and the short range projection method," J. Am. Cer. Soc. **2**, 977 (1919).

[6] K. S. Gibson, "A filter for obtaining light at wavelength 560 mμ," Nat. Bur. Stand. J. Research, **14**, 545 (1935); RP 785. Also, J. Opt. Soc. Am. **25**, 131 (1935).

experimenting with them. These experiments involve changes in temperature and in time, both of which affect the amount of volatilization of glass-forming oxides from the surface of the molten glass and also the dilution of the glass by solution of the pot in the glass. Since volatilization and pot solution both affect the index, we cannot expect a constant index until we can reduce them to a reasonably constant amount; this can probably only be done by establishing a definite time-temperature schedule for melting these glasses as we have done with the borosilicates.

The figures given above are based on measurements of index of refraction made on samples of glass taken directly from the pot after the glass is cold. A similar table based on measurements after the glass has been molded and annealed might be illuminating, but it would certainly be disconcerting because the refractivity of the glass after molding and annealing will, in general, undergo some change, depending on the time-temperature effect incident to final annealing. Since the conditions required for annealing glass depend on the dimensions of the piece, we use, in general, two schedules for annealing glass—one, for small blanks, in which the glass is heated to a temperature just below its softening point (to remove all effects of previous thermal treatment) and then cooled at progressively increasing rates; the other, for large prism blanks, in which the glass is heated to a similar high temperature and then cooled somewhat rapidly to a temperature about 100°C lower and held at this temperature for about 48 hours, after which final cooling is started. In the first case the refractivity may be increased by only a few points in the fourth decimal, but in the second case the refractivity is increased by at least one in the third decimal. One must, therefore, expect a greater change in index of large elements than of small elements made from the same kind of glass.

In view of the foregoing conditions, if an optical instrument maker is concerned with a definite knowledge of the refractivity of the glass he is to use, he should have no interest at all in the optical constants of the glass as it comes from the pot, but he should concern himself with its optical properties after the glass has been finally annealed. I know of at least one specification for optical glass in which the limits on refractivity are given as ±0.001. If the manufacturer makes glass near the upper limit and the glass is subsequently annealed at a low temperature, it is evident that the finished glass will have a higher index than the specified tolerance and probably elements made from such glass will not function properly.

The extent to which the time and temperature of annealing affects the index of refraction of some of the optical glasses has been reported by Tool[7] (see Table II).

In considering the figures in Table II it must be borne in mind that they are based on equilibrium conditions—that is, the maximum changes that can be obtained by prolonged treatment at given temperatures in the temperature ranges given. The increase in index of borosilicate crown is given as 0.000048 per degree C decrease in effective annealing temperature between 540° and 470°C. Heat treatment, if sufficiently prolonged at 500°C would increase the "ordinary" index from 1.517 to 1.51892, or approximately 0.002. For practical purposes it is not necessary to "anneal" glass long enough to reach Tool's equilibrium—it is only necessary to anneal it enough to remove most of the permanent strain

TABLE II.

TYPE OF GLASS	INCREASE IN REFRACTIVITY AND DENSITY PER DEGREE CENTIGRADE DECREASE IN EFFECTIVE ANNEALING TEMPERATURE		RANGE OF EFFECTIVE ANNEALING TEMPERATURE FOR WHICH VALUES WERE DETERMINED (°C)
	REFRACTIVITY	DENSITY	
Medium flint	0.000024	0.00016	350–460
Dense flint	.000036	.00027	360–440
Borosilicate crown	.000048	.00028	470–540
Ordinary crown	.000032	.00017	500–570
Light barium crown	.000047	.00033	500–570

(and its attendant birefringence), a treatment that involves less time than the establishment of equilibrium. Hence, in our ordinary annealing of large prism blanks (previously referred to), the increase in refractivity is only about one-half that which might be obtained at equilibrium.

It has been suggested that this time-tempera-

[7] "Physical properties of glass as affected by thermal treatment (including annealing)." Misc. Pub. Nat. B. S. 102, 24 (1929).

ture effect on refractivity might be taken advantage of to yield exactly the desired index. This could be done, but its accomplishment presupposes a definite knowledge of the amount of time-temperature change in refractivity and might, under some circumstances, involve more time and careful temperature control than could be justified. In special cases, as for refractometer prisms, it is used successfully.

In this connection, we were asked to reanneal some blanks that had been obtained for making several objectives, with identical optical characteristics, to be used in making precision measurements. The glass, when received, had an average index (n_c) of 1.565370, but the refractivity was not sufficiently uniform from piece to piece to warrant its use. Our problem was to reanneal it without materially changing its index and at the same time bring the interblank spread within reasonable limits. Tests indicated that it would be necessary to heat the glass at 491°C for 8 days and then cool at the rate of about 4° per hour. Precautions were taken to reduce temperature gradients in the furnace to a minimum. As received, the maximum difference in index between blanks was 63×10^{-6} or nearly 5 times the designer's tentative permissible limit (the maximum deviation from the mean was 37×10^{-6}). By reannealing, the maximum deviation was reduced to 3×10^{-6} and final refractivity was only 17×10^{-6} higher than the original average n_c.[8]

[8] L. W. Tilton, A. N. Finn and A. Q. Tool, "Cause and removal of certain heterogeneities in glass," Nat. B. S. Sci. Pap. **22**, 719 (1928); S572.

Another question that frequently confronts us relates to the impression that foreign made optical glass is superior in quality to that made in America. To this there is only one answer—there is no significant difference in the optical behavior of glass from any of the several possible sources provided that the glass is free from striae, that it is properly annealed and that it has the desired indices of refraction. The geographic source of the raw materials is of no significance, provided they are sufficiently pure.

The present status of American activities in the production of optical glass is not to be belittled when we consider that, twenty years ago, there had been practically no optical glass made in this country, that Americans had little or no detailed information regarding the technique of making such glass, and that some of the essential raw materials were not available. In contrast, we can now safely say that all the necessary raw materials are or can be produced domestically, that a large amount of pertinent technical information is available, that there is a considerable personnel experienced in the manufacture of optical glass, and that there are now in operation at least two domestic plants where good optical glass, for the most exacting purposes, is being made. When we consider all these facts, I think we are justified in concluding America has an established optical glass industry and that American manufacturers of optical instruments are definitely assured of a constant, reliable and adequate domestic supply of optical glass that will meet all their requirements.

A Photoelectric Transmission Spectrophotometer for the Measurement of Photosensitive Solutions*

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(Received September 22, 1937)

This spectrophotometer was designed specifically to measure in the visible region the absorption spectrum of visual purple, the photosensitive substance of the retinal rods. It is independent of both the photoelectric cell and amplifier characteristics, relying only on the law of crossed polarizing prisms. The sensitivity of the detecting system is high enough so that the measuring light produces no detectable effect upon the measured solution. The entire system can measure a transmission of 1 percent to a precision of about 1 percent.

THE principles upon which this spectrophotometer operates are briefly as follows: Monochromatic light, after passing through three parallel Glan-Thompson prisms and the sample to be measured, falls on the cathode of a photoelectric cell. The resulting photoelectric current passes through a high resistance in the grid circuit of an FP 54 amplifier. The potential drop across this high resistor is balanced out by means of an uncalibrated potentiometer so that the amplifier galvanometer reads zero. The sample is then removed from the monochromatic beam and the balance restored by reducing the intensity of the light incident on the photo-cell by means of a rotation of the middle polarizing prism. The percentage reduction of the light intensity can be computed from the angle through which the prism has to be rotated to restore the balance. This percentage reduction is taken to be equal to the absorption of the sample.

The arrangement of the apparatus is sketched in Fig. 1. It consists of the source; a condensing lens; two monochromators, in zero dispersion arrangement; the photometer; a light tight box in which the sample to be measured can be shuttled in and out of the light beam; the photo-cell; and finally, the amplifier.

MONOCHROMATOR

The source is a 6–8 volt, 32 candlepower automobile headlight lamp operated on a 6 volt storage battery. An image of the filament is projected on the entrance slit of the first monochromator. The exit slit of this monochromator is removed, and the spectrum falls in the plane of the entrance slit of the second monochromator. Both monochromators are of the 90° constant deviation type. In use the slits of the second monochromator are of equal width and set to transmit a spectrum band of 2 to 3 mμ in width. The entrance slit of the first monochromator, however, is kept fixed at an opening that transmits 3 mμ at a wave-length of 400 mμ.

PHOTOMETER

The photometer consists of three Glan-Thompson prisms. The two outer prisms are stationary and parallel to each other. The middle one is mounted in a carefully fitted conical bearing and can be rotated about its axis. An engraved scale and vernier permits the determination of this rotation to one minute of arc. In this arrangement where the intensity is pro-

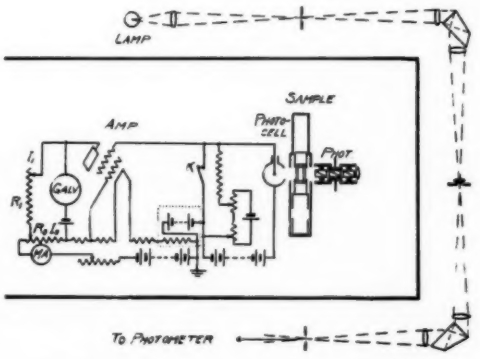

FIG. 1. The diagram of the arrangement of the spectrophotometer.

* Publication assisted by the Ernest Kempton Adams Fund for Physical Research of Columbia University.

portional to the $\cos^4$ of the angle, one minute of arc corresponds to about 0.3 percent of the transmission when it is only 1 percent itself.

Both outside prisms are in mounts that can be removed and replaced in the apparatus so that they come back to the same angular position to within one minute of arc. Each prism is then individually adjusted in its mount to maximum extinction when the middle one is at 90°.

Three polarizing prisms were found necessary because (1) light leaving the monochromator is partially plane polarized. Therefore the first prism must be fixed, since any rotation of it will cause a change in the intensity of the light. (2) The photoelectric cell was found to be differently sensitive to light polarized in different meridians. Therefore the incident light has to be either fixed in its plane of polarization or completely depolarized. The former is more readily achieved and is more conservative of light. In addition the $\cos^4$ of the angle yields a somewhat more open density scale at high densities than does the $\cos^2$ functions.[1]

A substitution photometer demands that the source and detector remain constant throughout the period of a measurement. To operate this photometer by means of visual settings of the scale is both tedious and time consuming. To avoid this, several mechanical stops were incorporated so that only one reading of the scale is necessary for each determination.

Figure 2 shows the arrangement of these stops. The large disk is a stationary scale cover and holds two verniers, 180° apart, near its periphery. *A* is the arm by which the center prism may be rotated. *B* is a block of bronze fastened on to *A*. A V-groove is cut transversely on the upper and lower surfaces of this bronze block. *C* is one of three spring stops that engages the arm *A* by snapping into the groove in the lower face of *B*. These stops are similar to those used on the multiple nosepieces of compound microscopes. They consist of T-shaped pieces of flat spring steel, to which a steel wedge is riveted at the lower end of the vertical arm; and the whole unit is mounted by means of two screws through the ends of the horizontal arm. Measurements show that with such stops the arm *A* is brought back to the same position to within 0.007 mm upon repeated settings. At the radius of the stop used here, namely 160 mm, one minute of arc is equivalent to 0.047 mm. Stop *C* is fastened to the periphery of the scale cover in such a position that the scale reads 0°:00′ when *A* is engaged with it. Thus the three prisms may be set parallel rapidly without reading the scale. *D* is another spring stop that also engages the bottom groove of *B* and is mounted so that the scale reads 55°:47′ when it engages the arm *A*. At this scale value the intensity of the transmitted light is exactly 0.1 of the maximum. The reason for this stop will become clear presently when the methods of operating this instrument are described.

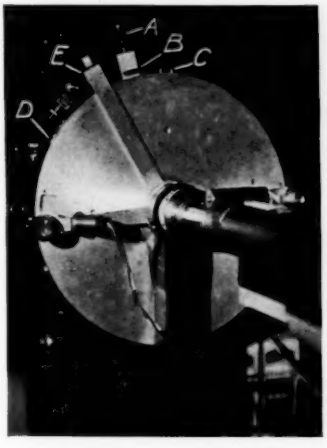

FIG. 2. A photograph of the photometer showing the arrangement of the mechanical stops.

E is an arm that can be rotated about the optic axis of the photometer. It can be locked into any position by means of the thumb screw at its end. A section of a circular ring is fastened near the end of this arm and over it is a circular slide that may be moved by means of a tangent screw and spring. To the lower surface of this slide a third spring stop is fastened so that it engages with the upper groove of *B*. When *A* is engaged with this stop, both arms may be moved to any position together. After locking *E* by means of the thumb screw, a fine adjustment is available by means of the tangent screw driving the stop slide. We thus have two fixed and one

[1] J. H. Dowell, J. Sci. Inst. **8**, 382 (1931).

variable scale position to which the middle prism can be set without looking at the scale.

There are two ways in which this photometer is used. In the first one the maximum intensity (when A engages C) passes through the sample and falls on the photoelectric cell. The potential across the grid resistor is balanced out by means of the potentiometer in the grid circuit. The sample is then removed from the beam; A is engaged with E, and together they are rotated to an approximate balance; E is locked into position; and exact balance achieved by means of the fine adjustment. A check on the constancy of the source and detector is rapidly achieved by replacing the sample in the beam and moving A back to C; removing the sample and returning A back to E. The angle, θ, is then read at the vernier. The transmission is given by the equation: $I_t/I_i = \cos^4\theta/\cos^4 0° = \cos^4\theta$; and the density by: $D = -\log(I_t/I_i) = -4 \log \cos\theta$.

The second method involves the use of stop D and is used whenever photosensitive solutions are to be measured. A is set at D and the photocurrent balanced with the sample removed from the beam. The sample is then inserted and the balance restored by uncrossing the prisms. Again E is used in the same way as in the first method giving an opportunity for rapid checking. The angle, θ, can lie only in the region between 0°:00′ (position C) and 55°:47′ (position D), limiting this method to the measurement of densities less than 1. This is no serious limitation when solutions are to be measured. Transmission under these circumstances is given by:

$$I_t/I_i = \cos^4 55°{:}47'/\cos^4\theta = 0.1/\cos^4\theta,$$

and density by:

$$D = -\log(I_t/I_i) = 4 \log \cos\theta - 4 \log \cos 55°{:}47'$$

and since

$$4 \log \cos 55°{:}47' = -1.00$$

$$D = 4 \log \cos\theta + 1.00.$$

The second method was adopted for use with visual purple solutions because it was found that it took much less time to balance the amplifier by rotating the polarizing prism than by adjusting the potentiometer. In the first method the sample is in the path of the light during electrical balancing, while in the second method it is exposed to the light during the optical balancing. In addition, the sample is exposed to the maximum intensity of the light throughout in the first method, while in the second one it is exposed to a lower intensity. Both these factors help to minimize the effect of the measuring light on the sample.

Sample Holder

The sample holder consists of a light-tight oblong box in which there is a shuttle with two compartments. Either one may be brought into the path of the measuring beam by means of a rod sliding in a tight sleeve. The end of this rod may be seen to the left of the vernier in Fig. 2. The internal arrangement of this box is such that when the proximal compartment of the shuttle is in the path of the light, the distal compartment is entirely light tight. This permits the removal of the entire box for loading of photosensitive samples in the dark room. Each compartment of the shuttle can accommodate samples up to 75×75 mm: the distal one up to 25 mm in thickness, and the proximal up to 30 mm in thickness. For solutions, the Zeiss fused glass cells of 5, 10, and 20 mm internal depth are used.

The Photo-Cell Circuit

The photo-cell and its related circuit are enclosed in a light-tight shielded box. The photo-cell is the RCA U.X.-867. It is of the Cs on Ag type, gas filled with a gas amplification factor of about 2 at 90, and 9 at 180 volts. It is used with a maximum potential of 90 volts. The anode is connected to the grid in order to keep the capacity of the grid circuit at a minimum. The grid resistor is as high as the capacity of the grid circuit will permit, namely 10^{10} ohms. Higher values of the grid resistor increase the time constant of the circuit beyond convenient values.

The high resistor is of the moulded type made by S. S. White. Like all high resistors this one exhibits polarization phenomena to some extent. This property is extremely bothersome. Let us assume that in operating this instrument by the second method outlined above, there is a photocurrent of 10^{-10} amperes flowing through the photo-cell. There will then be a potential drop of 1 volt across the resistor. This potential is

then balanced by an equal one of opposite sign on the potentiometer. The next manipulation is to shuttle the sample into the beam. During this period the beam is completely obstructed for a short time causing the potential across the high resistor to fall to zero. Upon readmission of the full beam into the photo-cell, it is found that the potential across the resistor reaches its previous value very slowly, the time depending upon the value of the potential through which it had been swung. To avoid this the shorting key, K (Fig. 1), was installed. Since at balance the potential across the potentiometer is equal and opposite to that across the resistor, there is no potential difference across the key. If now we short the key before interrupting the light beam, the initial potential across the resistor is maintained by the potentiometer even though the photocurrent falls to zero. This key is operated by means of a solenoid controlled by the sample holder shuttle, it being open only when the shuttle is at either extreme position. It is, of course, this property of the high resistor that contributes to the length of time necessary to establish an initial balance by means of the potentiometer.

Amplifier

The amplifier circuit is a slightly modified form of the one designed by Soller.[2] The modification is surrounded by a dotted line in Fig. 1. R_0 is the critical resistance to establish the balance in his circuit. He has shown in his equation (7) that the necessary precision in the value of R_0 depends upon the I_1 vs. I_0 characteristic of the tube. The value of R_0 is least critical when the ratio

$$\frac{\Delta I_0/\Delta I_1}{I_0/I_1}$$

approaches 1. His Pliotrons No. 1 and No. 2 have the ratio value of about 0.5, while No. 4 has the value of about 0.12. Several tubes examined by the author had much worse ratios, values between 0.02 and 0.03, necessitating an almost impossible precision in the value of R_0. These low ratios may be improved by increasing I_1 or decreasing ΔI_1 in some manner. The latter is accomplished here by the modification which gives I_0 a negative control over I_1 through greater grid potential control. The exact amount of additional grid potential control necessary can be determined readily from the E_g *vs.* I_1 characteristic of the tube. The exact value came out to be about 14 volts for the tube used in this amplifier. Since this additional control voltage has to be counter-balanced by an independent battery, a convenient value of 13.5 volts, corresponding to nine dry cells, was chosen. The resulting ratio turned out to be about 0.5.

There are two disadvantages to this arrangement. The first one concerns the use of an additional grid battery as well as a larger filament battery. Since the additional battery is entirely in the grid circuit, it must remain constant to within the desired precision of the amplifier. In the present case the highest constancy attainable in the source and photo-cell circuit is equivalent to about 10^{-14} amperes when the total photocurrent is about 10^{-10} amperes. This corresponds to about 10^{-4} volts in the grid circuit. A small "C" battery when enclosed in the shield to prevent rapid temperature changes maintained its potential to a constancy much greater than demanded by the constancy of the photocurrent. The probable limiting factor in the entire circuit is the constancy of the source, because when the light intensity is such as to give about 10 volts across the grid resistor, the best balance that can be maintained during a measurement corresponds to about 10^{-3} volts, while a balance of 10^{-4} volts can be achieved when the grid potential is only about 1 volt. This means probably that the source is constant only to about 0.01 of 1 percent and limits the precision of density measurements to 1 percent when the density is 2.

The second disadvantage is the fact that the input terminals of the amplifier are about 13.5 volts above ground potential. In the present apparatus this is of no moment since the input circuit is more or less permanently connected. But this might be a serious source of trouble in an amplifier for general use.

Accuracy

The accuracy of this spectrophotometer was checked by means of measurements on three colored glasses standardized by the National

[2] W. Soller, Rev. Sci. Inst. **3**, 416 (1932).

Bureau of Standards. The transmissions as given by this apparatus were within the uncertainties of the standard values, though most of them were above those given by the National Bureau of Standards. The most probable cause for this small discrepancy in the transmission values lies perhaps in the greater compactness of the photometer, sample, and detector in this arrangement as compared with that used by the National Bureau of Standards.[3] Due to the greater proximity of the various air-glass interfaces, the multiple reflections may build up to an appreciable value on the detector.

[3] K. S. Gibson, J. O. S. A. **21**, 564 (1931).

This machine has been in use in this laboratory now for about two years and has enabled us to measure extremely small concentrations of visual purple. We have been able to detect and measure the course of the regeneration of visual purple in solution after bleaching[4] as well as to estimate its molecular weight by measuring its rate of diffusion[5] through a porous membrane where concentrations having a density of only 0.03 at a wavelength of 500 mμ were measured to a precision of 2 to 3 percent.

[4] S. Hecht, A. M. Chase, S. Shlaer, C. Haig, Science **84**, 331 (1936).

[5] S. Hecht, A. M. Chase, S. Shlaer, Science **85**, 567 (1937).

An Optical Paradox*

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(Received November 26, 1937)

IT is well known that with ordinary glasses a thin lens system cannot be corrected for three colors. Since the question of color correction and the secondary spectrum has again been raised through the development of color photography on one hand, and infrared and ultraviolet photography on the other, the author has tried to study the conditions for color correction in optical systems with finite distances. It is also well known that in systems with finite distances there are two first-order chromatic aberrations, namely, longitudinal color aberration, and the error of magnification.

In the present paper we shall investigate only the latter error, i.e., the error of magnification, particularly for an infinite object. In other words, we shall investigate the variation of the focal length with the wave-length. Here we find a paradoxical situation, which may be described as follows:

If we have an optical system corrected for two, but not for three colors, can we add a supplementary system such that the entire system is corrected for three colors? The answer is in the affirmative. We have to add a system whose focal length for the third order is equal to the color-corrected focal length of the first system. If we place the second system at the focal point of the first, we obtain a system corrected for three colors which has the same focal length as the first.

The paradox of the whole situation consists in the fact that although the supplementary lens is independent of the color correction of the first lens for the third color, it corrects for the third color.

This fact, which is of considerable importance for the color correction of optical systems, is one of the results revealed in this present study, which constitutes the basis for a more comprehensive investigation of the color properties of optical systems.

* Communication No. 651 from the Kodak Research Laboratories.

I. DEFINITION

Given an optical system we want to characterize its color qualities. For this purpose let us choose one color as the *fundamental* color, another color as the *primary* color, and a third color as the *secondary* color, and designate magnitudes for the fundamental color by letters without subscripts, giving to the magnitudes for the primary and secondary colors the subscripts (I) and (II). Then we introduce expressions v and w by means of the following equations:

$$(\phi_I-\phi)/\phi=v, \quad \text{or} \quad \phi_I=\phi(v+1),$$
$$(\phi_{II}-\phi)/\phi=w, \qquad \phi_{II}=\phi(w+1), \tag{1}$$

where ϕ,ϕ_I, ϕ_{II} are the ~~refractive indices~~ powers for fundamental, primary, and secondary colors, respectively.

We call v the *primary relative dispersion* (abbreviated p.r.d.) and w the *secondary relative dispersion* (s.r.d.), and these expressions will be used throughout the paper.

For those who are accustomed to the terminology introduced by Abbe, we might mention that

$$1/v=\nu \tag{2}$$

which is approximately equal to the nu value of Abbe (except that we don't bring three colors into this expression) and that

$$w/v=\alpha \tag{3}$$

can be considered as the partial dispersion of our systems.

Equation (1) indicates that the focal length is corrected for the primary color, if and only if $v=0$; the focal length is corrected for three colors, if and only if $v=w=0$.

It would be convenient, if we could call a system with $v=0$ an achromat, and a system with $v=w=0$ an apochromat; but, since E. Abbe has put an additional implication on the use of the word apochromat (correction of sine condition) we will call a system with $v=w=0$ a triachromat.

Let us give some examples, in which v and w are calculated:

(a) The thin lens in air

We have, if ρ_1 and ρ_2 are the curvatures of the surfaces (reciprocal radii),

$$\phi=(n-1)(\rho_1-\rho_2) \tag{4}$$

and find that

$$v=(n_I-n)/(n-1), \quad w=(n_{II}-n)/(n-1) \tag{5}$$

as glass constants, which depend neither upon the form nor upon the focal length of the system.

(b) The single surface

Let us now investigate a surface separating two media with refracting indices n and n'. We find:

$$\phi=(n'-n)\rho,$$

which gives:

$$V=\frac{v'(n'-1)-v(n-1)}{n'-n}, \qquad W=\frac{w'(n'-1)-w(n-1)}{n'-n}. \tag{6}$$

If the first medium is air, we have,

$$n=1, \quad v=w=0, \quad \text{or} \quad V=v', \quad W=w'.$$

If the second medium is air, we have

$$n'=1, \quad v'=w'=0 \quad \text{or} \quad V=v, \quad W=w.$$

That means, that the p.d. and s.r.d. of the surface are equivalent to the r.p.d. of the glass. (b) can be used to investigate the color effect of a cemented surface as function of the color constants of the two glasses.

(c) The thick lens in air

The focal length is given by:

$$f=(n-1)(\rho_1-\rho_2)-(d/n)(n-1)^2\rho_1\rho_2. \tag{7}$$

Therefore,

$$V=v\frac{\rho_1-\rho_2-[d\rho_1\rho_2(n-1)(v+1)]/[n+(n-1)v]}{\rho_1-\rho_2-d\rho_1\rho_2(n-1)(1/n)}, \qquad W=w\times\frac{\rho_1-\rho_2-[d\rho_1\rho_2(n-1)(w+1)]/[n+(n-1)w]}{\rho_1-\rho_2-d\rho_1\rho_2(n-1)(1/n)} \tag{8}$$

where w and v are the p.r.d. and s.r.d. of our glass.

We see that by choosing

$$d=(r_2-r_1)\frac{n+(n-1)v}{(n-1)(v-1)}=(r_2-r_1)\frac{n_I}{n_I-1} \tag{9}$$

we can form an achromatic, but not a triachromatic single lens. For an achromatic thick lens, we get:

$$\phi=(n-1)(\rho_1-\rho_2)(v/n(v+1)). \tag{10}$$

II. Combination of Thin Lenses

Let us assume that we have a combination of thin lenses without distances. The power of the combination is then given by

$$\Phi=\phi_1+\phi_2+\cdots+\phi_n. \tag{11}$$

From our definition formula (1) we get now:

$$\Phi V=\phi_1v_1+\phi_2v_2\cdots+\phi_nv_n, \qquad \Phi W=\phi_1w_1+\phi_2w_2\cdots+\phi_nw_n. \tag{12}$$

(a) Two thin lenses

Let us investigate first two thin lenses. We get

$$\Phi=\phi_1+\phi_2, \qquad \Phi V=\phi_1v_1+\phi_2v_2, \qquad \Phi W=\phi_1w_1+\phi_2w_2. \tag{13}$$

We can solve the first Eqs. (13) according to ϕ_1 and ϕ_2 and get:

$$\phi_1=\frac{v_2-V}{v_2-v_1}\Phi, \qquad \phi_2=\frac{V-v_1}{v_2-v_1}\Phi. \tag{14}$$

Introducing (14) into (13) we get:

$$W(v_2-v_1)=(v_2w_1-v_1w_2)+V(w_2-w_1) \quad \text{or} \tag{15}$$

$$v_2w_1-v_1w_2=W(v_2-v_1)-V(w_2-w_1). \tag{16}$$

If the primary spectrum is corrected ($V=0$), we have, for the secondary spectrum,

$$W=\frac{v_2w_1-v_1w_2}{v_2-v_1}. \tag{17}$$

Now, it is an experimental fact that for most glasses there is a linear connection between v and w (König), i.e.,

$$w=Av+B, \tag{18}$$

with constants A and B independent of the glasses. Glasses of this kind are called ordinary glasses, and it is the endeavor of the glass maker to find glasses which do not follow this relation. From (17), we get for ordinary glasses:

$$W=B. \tag{19}$$

That means that the secondary spectrum for an achromat is constant and is independent of the choice of glasses. For an achromat, we have

$$\phi_1=\frac{v_2}{v_2-v_1}\Phi, \qquad \phi_2=\frac{-v_2}{v_2-v_1}\Phi, \tag{20}$$

or

$$\phi_2=-\frac{v_2}{v_1}\phi_1, \qquad \Phi=\frac{v_1-v_2}{v_1}\phi_1. \tag{21}$$

If, for all glasses, we plot w against v, we get the ordinary glasses on one line. Eq. (7) indicates that two glasses can give a corrected secondary spectrum if, and only if, the connection line between the two points indicating the glasses goes through the origin.

(b) Three thin lenses

We have

$$\begin{aligned} \Phi&=\phi_1+\phi_2+\phi_3,\\ V&=\phi_1v_1+\phi_2v_2+\phi_3v_3,\\ W&=\phi_1w_1+\phi_2w_2+\phi_3w_3. \end{aligned} \tag{22}$$

The system is trichromatic for $V=W=0$. That gives:

$$\phi_1=\Phi\frac{v_2w_3-v_3w_2}{\begin{vmatrix}1&1&1\\ v_1&v_2&v_3\\ w_1&w_2&w_3\end{vmatrix}}, \qquad \phi_2=\Phi\frac{v_3w_1-w_3v_1}{\begin{vmatrix}1&1&1\\ v_1&v_2&v_3\\ w_1&w_2&w_3\end{vmatrix}}, \qquad \phi_3=\Phi\frac{v_1w_2-v_2w_1}{\begin{vmatrix}1&1&1\\ v_1&v_2&v_3\\ w_1&w_2&w_3\end{vmatrix}}. \tag{23}$$

We see that the condition for a triachromat is that in our diagram the three glasses chosen do not lie on a line. The powers are smaller and, therefore, the curvatures and the image errors are smaller, the bigger the area of the triangle.

Therefore, achromatic correction cannot be achieved with ordinary glasses.

In general, we get from (12), using ordinary glasses (18),

$$W=AV+B, \tag{24}$$

which means that we cannot correct the secondary spectrum in a thin lens system with ordinary glasses.

III. System of Two Components with Finite Distance

Let us now consider a system with two components and finite distance d of the nodal points.

We get the well-known formula:

$$\Phi=\phi_1+\phi_2-d\phi_1\phi_2. \tag{25}$$

From (1) we find,

$$\begin{aligned} \Phi V&=\phi_1v_1+\phi_2v_2-d\phi_1\phi_2(v_1+v_2+v_1v_2),\\ \Phi W&=\phi_1w_1+\phi_2w_2-d\phi_1\phi_2(w_1+w_2+w_1w_2). \end{aligned}$$

We will investigate the conditions that make such a system triachromatic, i.e.,

$$V=W=0. \tag{26}$$

Let us introduce for abbreviation

$$\begin{aligned} v_2w_1-v_1w_2&=a,\\ v_1w_1(v_2-w_2)&=b,\\ v_2w_2(w_1-v_1)&=c. \end{aligned} \tag{27}$$

Then we find from (25), as a condition for triachromatic correction, if

$$\phi_1=\frac{a+c}{a+b+c}\Phi, \qquad \phi_2=\frac{a+b}{a+b+c}\Phi, \qquad d\phi_1\phi_2=\frac{a}{a+b+c}\Phi, \tag{28}$$

or, when we assume ϕ_1 as given, then

$$\phi_2=\phi_1\frac{a+b}{a+c},$$

$$\Phi=\phi_1\frac{a+b+c}{a+c}, \tag{29}$$

$$d\phi_2=\frac{a}{a+c}, \qquad d\phi_1=\frac{a}{a+b}.$$

Eq. (29) can serve to calculate ϕ_2, Φ and d, if we know the chromatic constants v and w of the two partial systems. Some special cases of formula (29) are of interest.

(a) Let us assume $a=0$, that is, that the partial dispersions of the two glasses are equal. Then we find:

$$d=0 \tag{30}$$

and obtain thus a special case of the case of two systems in contact.

Formula (29) simplifies to (21).

(b) Let us assume that b vanishes; that is possible only if one of the partial systems is an achromat. Without any loss of generality, we can assume that:

$$v_1=0. \tag{31}$$

That gives:

$$\begin{aligned} a&=v_2w_1,\\ b&=0,\\ c&=v_2w_1w_2, \end{aligned} \tag{32}$$

or

$$\begin{aligned} \phi_2&=1/1+w_2,\\ \Phi&=\phi_1,\\ d\phi_1&=1. \end{aligned} \tag{33}$$

The first equations can be written

$$\phi_{2II}=\phi_1. \tag{34}$$

The focal length of the second component for the third color must be equal to the focal length of the achromat. The second equation (33) means, that the focal length of the combination is equal to the focal length of the first part, and the third equation (33) shows that the second component is placed at the rear focal point of the first system.

We get the surprising result that the lens which we have to add is independent of w, the secondary partial dispersion of the first system; it depends only on the focal length and on the choice of color, certainly a paradoxical result.

(c) If we assume that $C=0$, then we obtain the same combination, in which only first and second parts are interchanged. We have:

$$\begin{aligned} v_2&=0,\\ \phi_2&=\phi_1(1+w_1),\\ \Phi&=\phi_1(1+w_1),\\ d\phi_2&=1. \end{aligned} \tag{35}$$

That means that the second component is achromatic, the power for the two colors is equal to the power of the first system, and the rear nodal point of the first system is the focal point of the supplementary lens. This case may have still greater practical value than the preceding.

An Instrument to Study the Intensity Variation of Transient Light Pulses

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(Received October 20, 1937)

INTRODUCTION

SINCE the general method of exposing photographic film consists in allowing a controlled pulse of light to fall upon the sensitive emulsion, the study of the form of these pulses is of interest to the photographic industry. A between-the-lens type of shutter is the usual mechanism for producing light pulses and the primary purpose of the instrument to be described is the study of these. However, focal plane shutters and photographic flash lamps have been studied with equal facility.

Similar instruments have been described by Reich and Marvin[1] and van Liempt and de Vriend.[2–5] However, the advent of cathode-ray tubes with long persistence screens has offered a medium upon which moderate speed transients may be made visible sufficiently long to be studied without the necessity of photographing the trace. In addition, a convenient and flexible timing method has been provided and a compact, portable instrument operating from an ordinary 60-cycle a.c. power line has been developed.

THE ELECTRIC CIRCUIT

The wiring diagram of the instrument is shown in Fig. 1. The light pulse to be studied is allowed to fall on the photo-cell, part of the photo-cell output being fed to the direct-coupled vertical amplifier. One vertical plate of the cathode-ray tube is directly connected to the plate of the amplifier tube while the other is connected to a biasing potentiometer for suitable vertical location of the screen pattern. This circuit provides a vertical deflection of the cathode-ray beam proportional to the instantaneous intensity of light upon the photo-cell.

Across the horizontal plates of the cathode-ray tube is a usual type of linear sweep circuit again with provision for proper horizontal location of the pattern. The sweep rate is controlled over a range of 1/5,000 to 1.5 seconds by the grid potential of the current limiting tube and the size of the condenser being charged. The grid potential of the gas triode is also controllable and in operation is set so that the condenser is just prevented from discharging through the tube. This grid is coupled to the photo-cell through the interlocking amplifier which converts the very first small amount of light from the pulse under observation into a voltage of the proper phase and magnitude to permit discharge through the gas triode. The time required for the discharge and deionization of the gas triode is very short, and consequently, only a minute fraction of the light pulse is not available for observation. In operation, this loss is negligible.

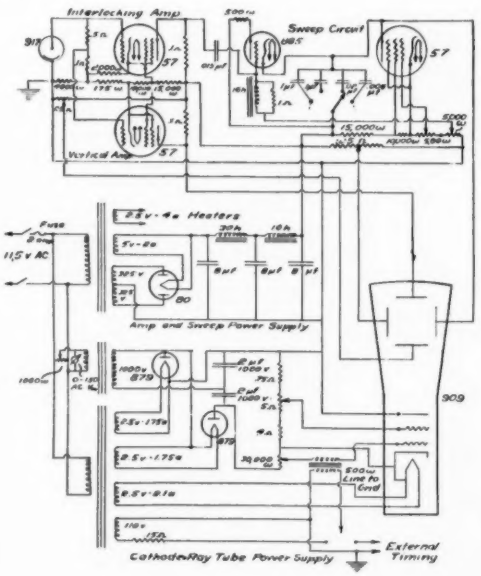

FIG. 1. Wiring diagram.

[1] H. J. Reich and G. S. Marvin, Rev. Sci. Inst. **2**, 814 (1931).
[2] J. A. M. van Liempt and J. A. de Vriend, Zeits. f. Physik **98**, 195–201 (1935).
[3] J. A. M. van Liempt and J. A. de Vriend, Physica **4**, 353–360 (1937).
[4] J. A. M. van Liempt and J. A. de Vriend, Philips Tech. Rev. **1**, 289–294 (1936).
[5] J. A. de Vriend, Zeits. f. wiss. Phot. **35**, 129–131 (1936).

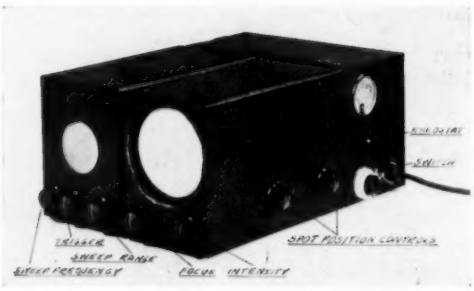

FIG. 2. Assembly of the completed instrument.

For stability of the sweep circuit, the coupling to the grid of the gas triode is through a high pass filter section that effectively prevents tripping of the sweep circuit by supply voltage fluctuations. The power supplies to the amplifiers, photo-cell, and cathode-ray tube are of usual types and require no explanation.

To superimpose a time standard upon the observed pattern, provision is made to insert a timing voltage into the grid circuit of the cathode-ray tube which varies the intensity of the beam. The result is that the screen pattern is traced out in a dotted line with the time interval between dots equal to the reciprocal of the frequency of the timing voltage. A switch selects either a 60-cycle voltage from one of the power transformers or an external source. Only one or two volts at negligible power are required from the external oscillator. A similar timing method has recently been described by Williams and Wolfenden.[6]

OPERATION

Figure 2 shows the assembly of the completed instrument with the various controls marked. The light pulse to be studied is allowed to fall upon the ground-glass screen and the resulting pattern observed upon the cathode-ray tube screen. Usually one or two trials are necessary to set the sweep rate properly, and to adjust the intensity of light. Thereafter, the phosphorescent pattern may be studied directly from the screen, or the sweep of the beam photographed.

In studying the phosphorescent trace, it is often desirable to accelerate the luminous decay of the screen pattern since the pattern may remain visible for as long as a half-hour. Exposure of the phosphorescent screen to radiant energy within the range of λ7500A to λ12,000A of reasonably high intensity effectively and quickly removes the visible glow from the screen.

Figures 3, 4, and 5 show representative curves obtained from a between-the-lens shutter and

[6] W. C. Williams and J. P. Wolfenden, Wireless Engineer **14**, 315–317 (1937).

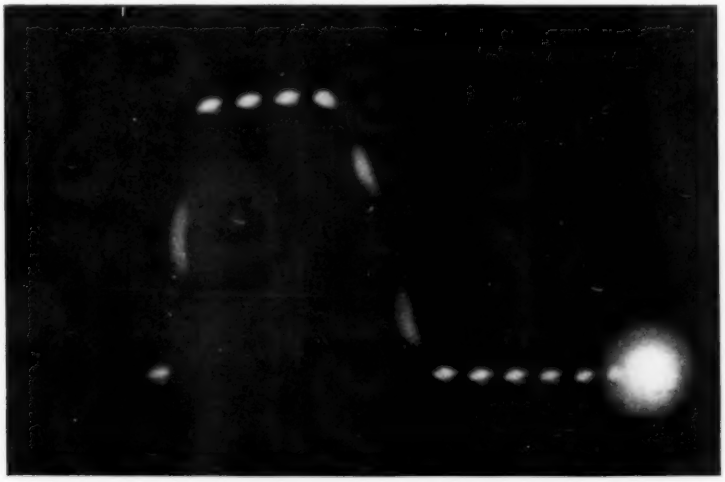

FIG. 3. Characteristic curve of shutter. Time voltage : 1000 c.p.s.

two types of photographic flash lamps. In the latter two cases, the horizontal sweep was initiated by the current supplied to the lamps.

Conclusions

This instrument has provided a convenient means of obtaining information that is, in general, difficult to secure. No examples of other applications have been given but wherever the time-intensity characteristics of a light pulse have been desired, the instrument has proven thoroughly adaptable.

Acknowledgment is due to Mr. A. B. Fuller of this department who conceived the idea of the phosphorescent screen as a recording medium for this application and who suggested the method of providing an accurate time scale.

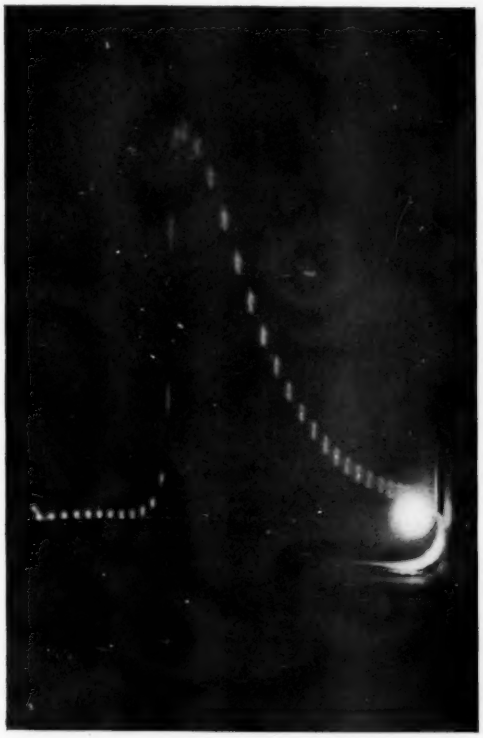

Fig. 4. Photographic flash lamp. Timing : 1000 c.p.s.

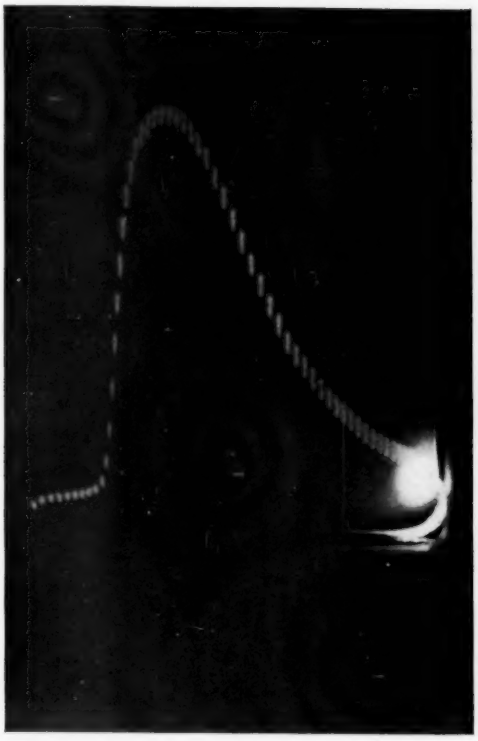

Fig. 5. Photographic flash lamp. Timing : 1000 c.p.s.

Necrology

Elihu Thomson

MARCH 13, 1937 marked, by the death of Elihu Thomson, the close of a long and extraordinarily useful life.

Born in Manchester, England, on March 29, 1853, he was brought, at the age of five, to this country by his parents. After graduation from the Central High School in Philadelphia he became a teacher and, at the age of 23, had gained the rank of professor.

He became keenly interested in electricity, and his early experiments at his high school foreshadowed many of the engineering developments with which he was soon to be actively connected. So great was the future he foresaw for electrical engineering, that he soon gave up teaching for the industrial field.

In that field he was a pioneer and a great leader. He was a prolific inventor, the recipient of about 700 patents. So many, so varied, and so important were his achievements, that no short selected list can give an adequate idea of the magnitude of his work. It was based on broad and thorough scientific knowledge, continuously augmented throughout his life. His approach to a problem and his methods of attack were those of a true scientist. His learning and interests were confined to no one field. Engineers, both electrical and mechanical, chemists, and astronomers, all recognized and esteemed him as an able and distinguished colleague. That recognition was world-wide, and the esteem was manifested by many and great honors conferred upon him. Among them were the Grand Prix and the Red Rosette of the Legion of Honor from France; the Hughes, Kelvin and Faraday Medals from England; the Medal of Honor of the Verein Deutscher Ingenieure from Germany; and from his own country the Edison, John Scott, Rumford, John Fritz, Elliott Cresson and Franklin Medals. He also received honorary degrees as follows: A.M., Yale; Ph.D., Tufts; D.Sc., Harvard and the University of Manchester, England; and LL.D., University of Pennsylvania. Professor Thomson was a member of many scientific and technical societies. He was a regular member of the Optical Society, his membership dating from 1931.

Known to the world as a great scientist, inventor and engineer, to those privileged to enjoy personal contact with his breadth of knowledge, his alertness and originality of mind, and his kindly and sincere character, he was also a highly honored and dearly loved philosopher, teacher and friend.

It is difficult to do justice to the greatness of his own achievements. It is impossible to evaluate the inspiration and help he gave to his associates, disciples, and friends.

Frederic E. Ives

FREDERIC EUGENE IVES, the inventor of many photographic and photomechanical processes, died at his home in Philadelphia on May 27, 1937. His great fund of general knowledge and his keen grasp of scientific principles were acquired almost entirely from reading and study after leaving school at the age of twelve because of the death of his father. Possibly it was this very lack of formal education that enabled him to combine with such conspicuous success the theory of the scientist and the practice of the artisan.

Frederic Ives was born near Litchfield, Connecticut, on February 17, 1856. His father, Hubert Leverit Ives, was a hard-working farmer who was never quite able to comprehend the latent desire for scientific knowledge that caused his young son to take more interest in mechanical devices than in the work on the farm. Although this early interest in mechanics was never lost, it became merged later with a love of the artistic which he acquired from his mother, Ellen Amelia Beach. The long and fruitful career that was to follow provided many opportunities for the satisfaction of these desires of his early childhood.

After the death of his father, young Frederic worked for a few months as a clerk in a country store. While still only thirteen, he applied for an apprenticeship in the printing office of the *Litchfield Enquirer*. He was accepted, despite his extreme youth, and served the full term of three years. At the completion of his apprenticeship, he left Litchfield and worked as a journeyman job printer for a firm in Ithaca, New York. Although a master of the printing craft, his active mind sought new fields of endeavor, and he turned to photography. After operating a portrait gallery for a short time, he applied for a position at Cornell University. In 1874, while still only nineteen, he was placed in charge of the photographic laboratory at the University.

The four years at Cornell provided the long-desired opportunity to perform experiments. The fruit of these experiments was the first commercially successful halftone process of photoengraving. The success of this invention, which revolutionized the art of illustration, led to his connection with a printing establishment in Philadelphia, where he worked as a photoengraver. He continued to experiment in a private laboratory, which he maintained in his home; and it was there, in 1886, that he developed the cross-line screen method of halftone reproduction, an improvement on his previous method. There have been no significant changes in this method during the more than fifty years of its extensive use. Indeed, the extraordinary skill of the inventor, both as a photographer and as a

printer, enabled him to make printing plates of a quality that has never been surpassed and is seldom approached.

In the course of his subsequent experiments, Ives made notable improvements in a number of optical instruments. Among the more important of these are the binocular microscope, the trichromatic colorimeter, the replica diffraction grating, and the parallax stereogram. These were minor excursions in a career that will ultimately be best known because of his work in the field of color photography and color reproduction. He was the first to show that the "color sensation" curves of Maxwell provide the basis for the selection of the three-color filters required for every process of three-color reproduction. His views on this subject provoked much criticism, and he was forced to become a party to a controversy that raged for many years. Now that the science of colorimetry has been developed and the theory of color reproduction has been placed on a firm foundation, it is of interest to note that his ideas, which seemed so absurd to the experts half a century ago, were basically sound. That he was able to arrive at the correct conclusions without the benefit of formal analysis calls attention even more forcibly to his extraordinary scientific insight.

Frederic Ives was elected to fellowship or honorary membership by many scientific societies and was awarded more than a score of medals for his numerous inventions. Although he secured more than seventy patents during his lifetime, some of the more important inventions, notably his halftone process, were unprotected. His inventions were never of the haphazard type but were characteristically the result of a scientific approach. That he realized the advantages of formal scientific training, which he was never able to receive, is evident from his autobiography, which he modestly titled *The Autobiography of an Amateur Inventor.*

The Board of Directors of the Optical Society of America created the Frederic Ives Medal in 1928. This medal is awarded biennially "for distinguished work in optics," in recognition of the remarkable career of Frederic Ives.

ARTHUR C. HARDY.

Edward Leamington Nichols

EDWARD LEAMINGTON NICHOLS, Ph.D., LL.D., Sc.D., professor of physics emeritus at Cornell University, an honorary member of the Optical Society of America and the first recipient of the Ives Medal of the Optical Society, died in West Palm Beach, Florida on November 10, 1937. He was born September 14, 1854 in Leamington, Warwickshire, England. Following graduation from Cornell University in 1875, he studied in Leipzig, Berlin, and Göttingen receiving the doctorate in 1879. Returning to America he was associated with Rowland at Johns Hopkins University where he held a fellowship and later with Edison at the Menlo Park Laboratory. In 1881 he became professor of physics and chemistry at Central University in Kentucky and in 1883, professor of physics and astronomy at the University of Kansas. In 1887, a little more than fifty years ago, he was called to the professorship of physics at Cornell where he was head of the department of physics until his retirement from active service as a teacher in 1919.

For Professor Nichols, scientific research was a necessity of life. His activity beginning when he was a student, continued uninterruptedly through years when facilities were poor and support meager, through years when editorial and administrative work made heavy demands upon his time, through years of leisure as professor emeritus. When failing sight forced him to rely on the observations of his associates his keen mind continued to devise experiments and to interpret results.

At the beginning of his academic career there was little interest or activity in scientific research in this country. It was not recognized as a necessary part of academic life and found support in only a few institutions. Nichols was always able to devise new and significant experiments that could be performed with the means available. An inspired teacher his single hearted interest in investigation soon attached to him a group of students which became always more numerous with the passing years until at the time of his retirement as a teacher, men and women who had come under the spell of his influence filled important posts in many laboratories throughout the country.

He constantly urged the importance of research and was active in efforts to improve the facilities available for it. In 1893 he founded the *Physical Review* having obtained the financial support of Cornell University. In collaboration with Ernest Merritt and Frederick Bedell he edited the *Physical Review* until 1913 when, its success assured, it was transferred to the American Physical Society. He was active in the group which founded the Physical Society in 1899 and served as its president in 1907. During his terms of office as president of the Physical Society, of Sigma Xi, and of the American Association for the Advancement of Science, Nichols took every occasion to further the recognition of scientific research as indispensable to the American university.

His researches deal with every branch of physics and many of its applications. The fields of physical and physiological optics, however, received the greatest attention. In the Menlo Park Laboratory he performed pioneer experiments in the photometry of incandescent lamps. Later his experiments in physiological optics laid foundations for the modern field of illumination and brought about his election as honorary member of the Illuminating Engineering Society and of the Association des Ingénieurs de l'Éclairage, Paris. In collaboration with Professor

Merritt he made spectrophotometric studies of luminescence and thereafter gave most of his attention to the field of luminescence. This work was supported by the Carnegie Institution of Washington of which he became a Research Associate. These investigations dealing with the intensity and quality of weak illuminations which were often of short duration made full demands upon his ingenuity in planning experimental procedures and his skill as an observer. The results of his researches brought him many honors, among them the Frederic Ives Medal of the Optical Society of America, the Elliott Cresson Medal of the Franklin Institute, and the Rumford Medal of the American Academy of Arts and Sciences of which academy he was a Fellow. He was a member of the American Philosophical Society, the American Academy of Science and of many other scientific and educational institutions.

An extensive traveler he had many acquaintances and as many friends. Honors and participation in important affairs in no way changed his relations to his students nor the concentration of his attention on his own research. Steadily through the years by administrative effort, by the accumulated results of his own researches, but most of all by the enthusiasm which he imparted to his students, Nichols has made contribution to the development of scientific research which one may not estimate. The momentum which the impact of his life has imparted to American science persists.

No words of description can so clearly portray the spirit which animated him as teacher and investigator as do words which he himself uttered before a large company of colleagues and former students gathered to do him honor at the time of his retirement.

"It has been delightful—unspeakably delightful, that life which comes from the study of science. What I would like to say, among the thousand things which I would like to say and cannot, is that you must not be content with the things the generation that is passing away had to be content with. It is for you to do greater things and more important things than we have done. The things are crying to be done and the world is crying out to get them done. If Cornell is to be what we all hope and believe she is to be, it can only be through the endless strivings of the imagination, through ceaseless labors and great creative art. It can only be by the highest efforts of everybody who has a mind to do anything whatsoever. Then we can look back upon the crude efforts of those who went before and while we may smile, we may at least believe that they looked forward to the things they could not accomplish but which you shall accomplish."

CARLETON C. MURDOCK